

Variation in the shape of the human medial meniscus

C. Kinley Russell¹ (kinley.russell@jhmi.edu) & Adam D. Sylvester¹

¹Center for Functional Anatomy & Evolution,
The Johns Hopkins University School of Medicine, Baltimore, MD

Purpose

The knee has been the subject of a substantial amount of anatomical research due to its role in locomotion and its susceptibility to injury. The menisci are important to the function of the knee as they serve to distribute compressive loads and facilitate controlled mobility.¹⁻² The shape of knee structures is closely tied to their function. Previous work has analyzed shape variation in bony knee surfaces, e.g.³⁻⁴ but meniscal shape variation is poorly understood. Here we examine shape variation of the medial meniscus in relation to biological sex and body size in a human sample.

Sample

The knees of 61 cadaveric individuals (34 female, 27 male) were dissected to expose the menisci and their insertions. These individuals ranged in age from 56-97 (mean: 79). Knees with total knee replacement or advanced osteoarthritis were excluded from the sample. Left knees were selected preferentially when both knees were appropriate for inclusion.

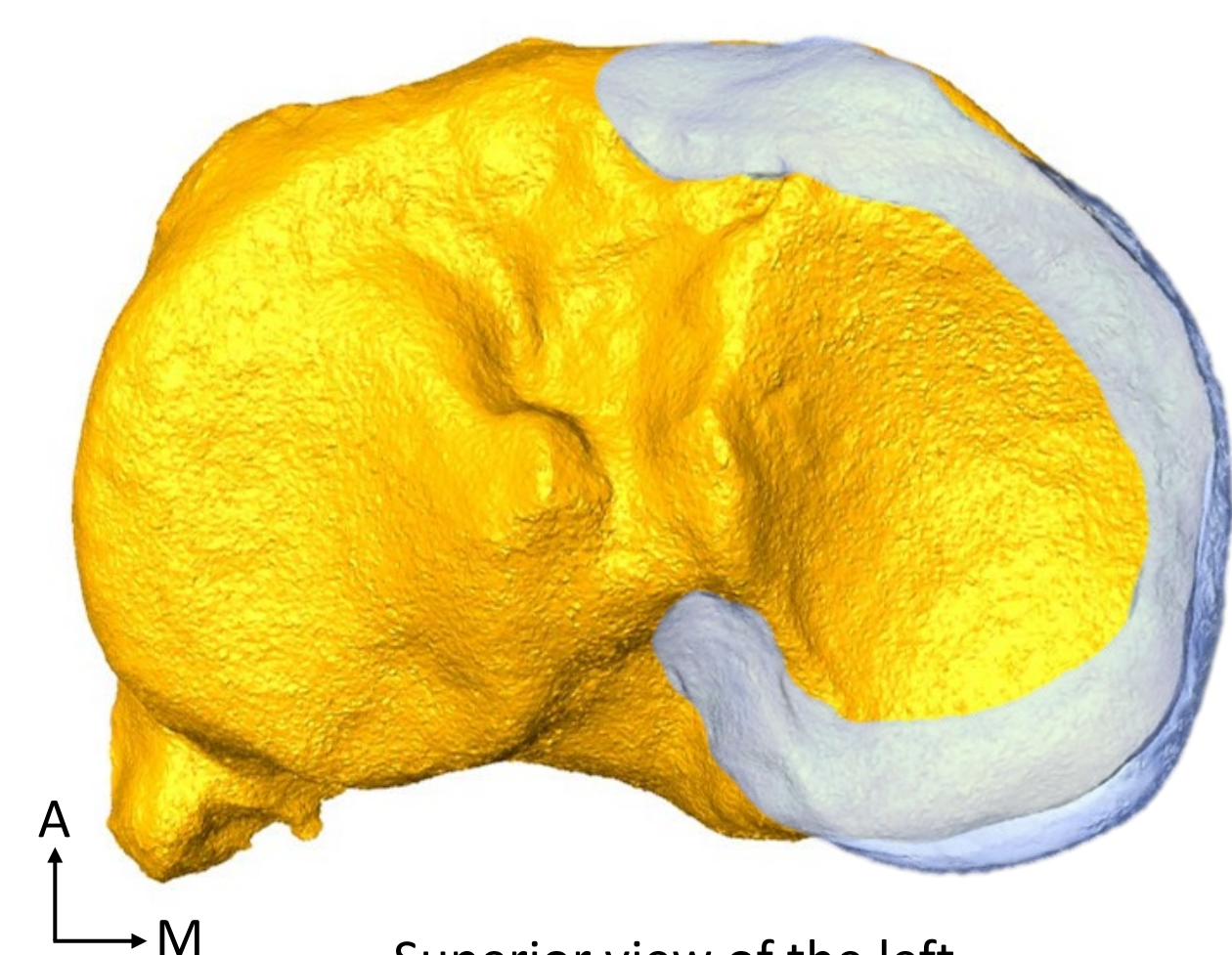
Methods

Surface Models

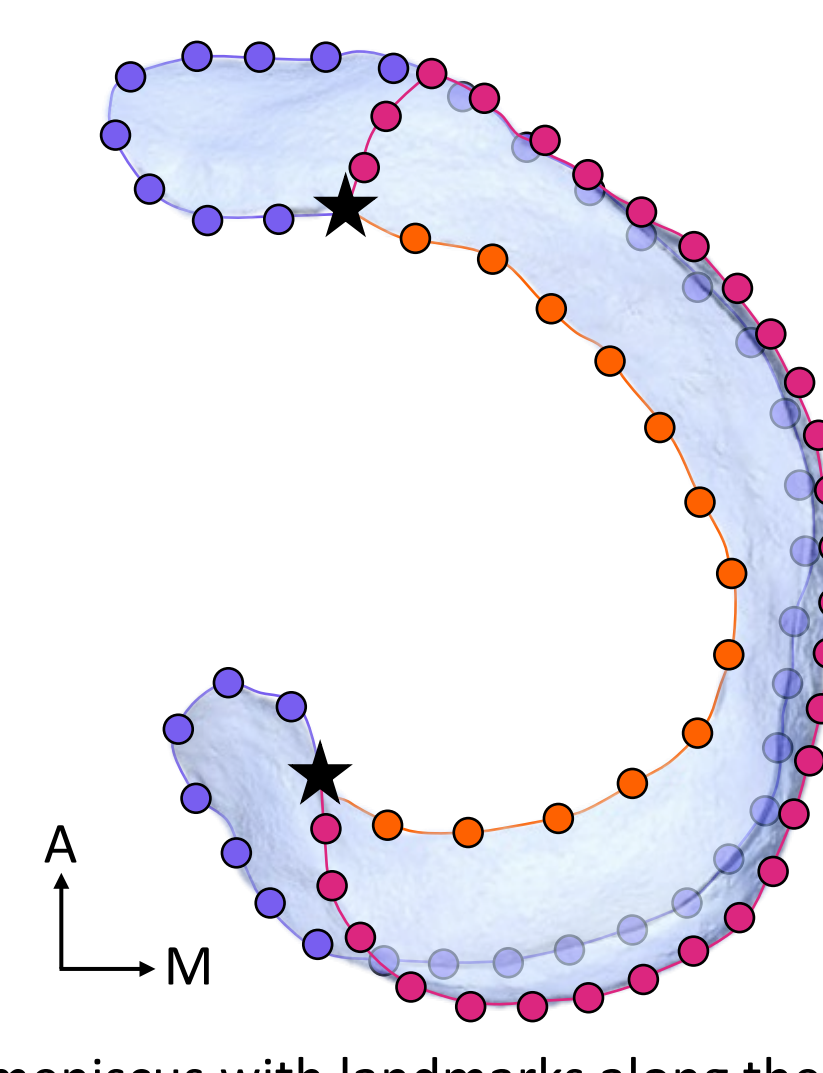
Photogrammetry and blue light scanning were used to generate surface models for each knee. Meniscal models were created by merging scans of the menisci with scans of the tibial plateau. Proximal tibiae from 38 individuals were photographed from 65 positions using a Canon Coolpix camera set to the macro setting. Photographs for each individual were masked and aligned to build a surface mesh using Agisoft Metashape.⁵ Proximal tibiae from 23 individuals were mounted to a rotating stand and scanned using an Artec Space Spider; surface models were automatically reconstructed using the real-time fusion setting in Artec Studio 16.⁶

Shape Analysis

Landmarks (n=81) were placed along the inner, outer upper, and outer lower edges of each meniscus in Avizo.⁷ The landmarks along each meniscal edge were then evenly distributed in MATLAB.⁸ Following Procrustes superimposition, landmark configurations were analyzed using principal components analysis and resampling with replacement.



Superior view of the left proximal tibia (yellow) with the medial meniscus (blue).

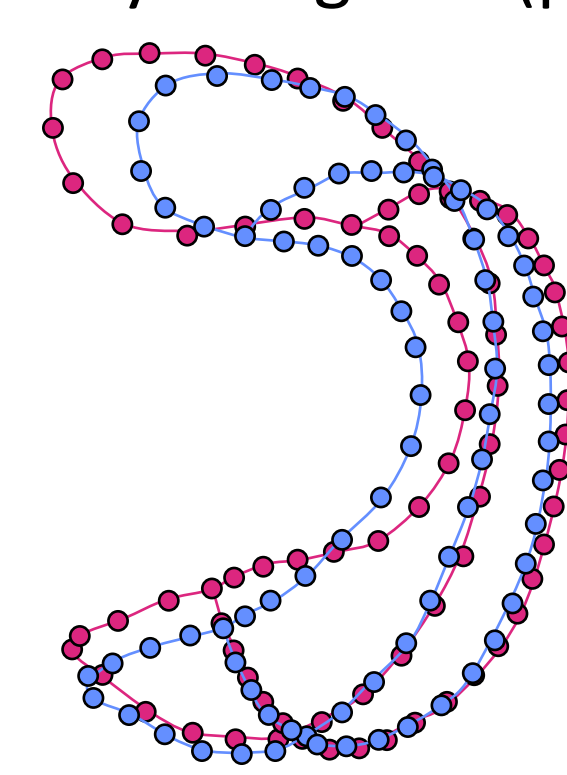


Medial meniscus with landmarks along the outer upper (●), outer lower (●), and inner (●) margins as well as at their anterior & posterior meeting points (★).

Results

Shape Variation by Principal Component

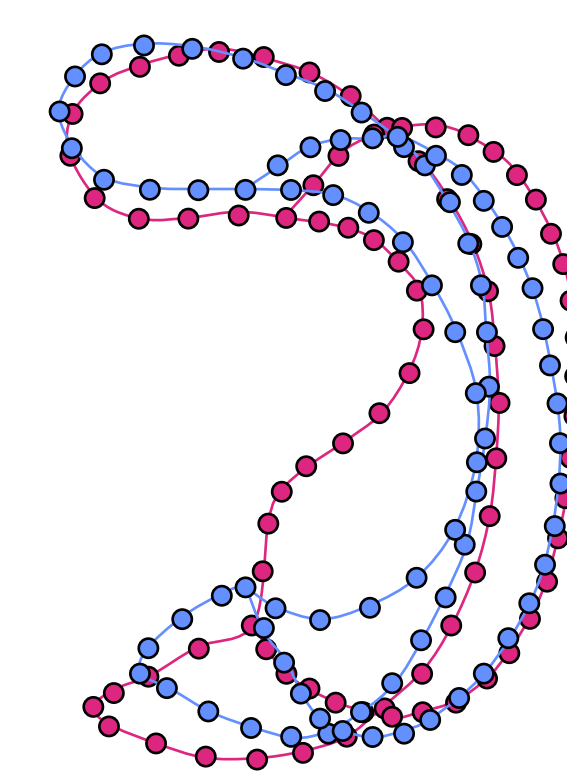
The first three principal components (PCs) explain over 72% of variation in the shape of the medial meniscus. Outlines demonstrating the variation in shape captured at two standard deviations positive (blue) and negative (magenta) for the first three PCs are included below. Though the overall shape of the medial meniscus does not differ significantly in males (♂) and females (♀) in this sample ($p=0.19$), males and females do differ significantly along PC2 ($p=0.01$).



PC1

Percent variance: 52.7%

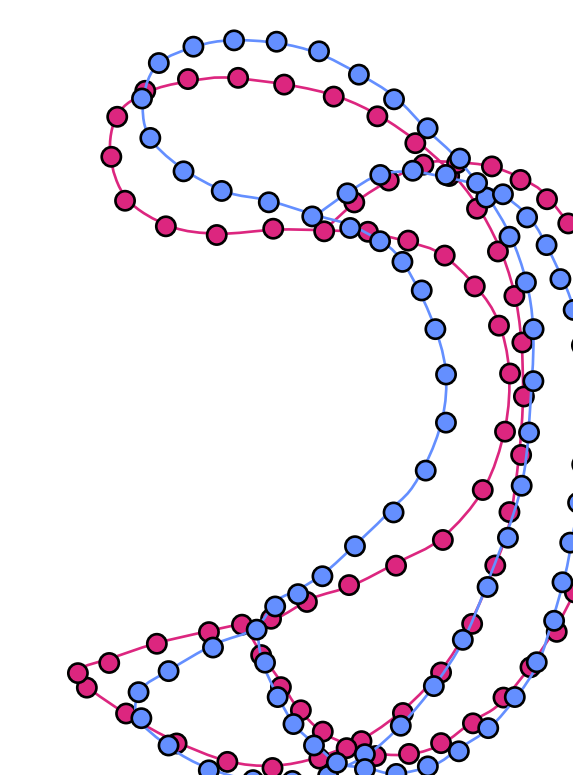
F & M shape significantly different?: No ($p=0.48$)



PC2

Percent variance: 11.9%

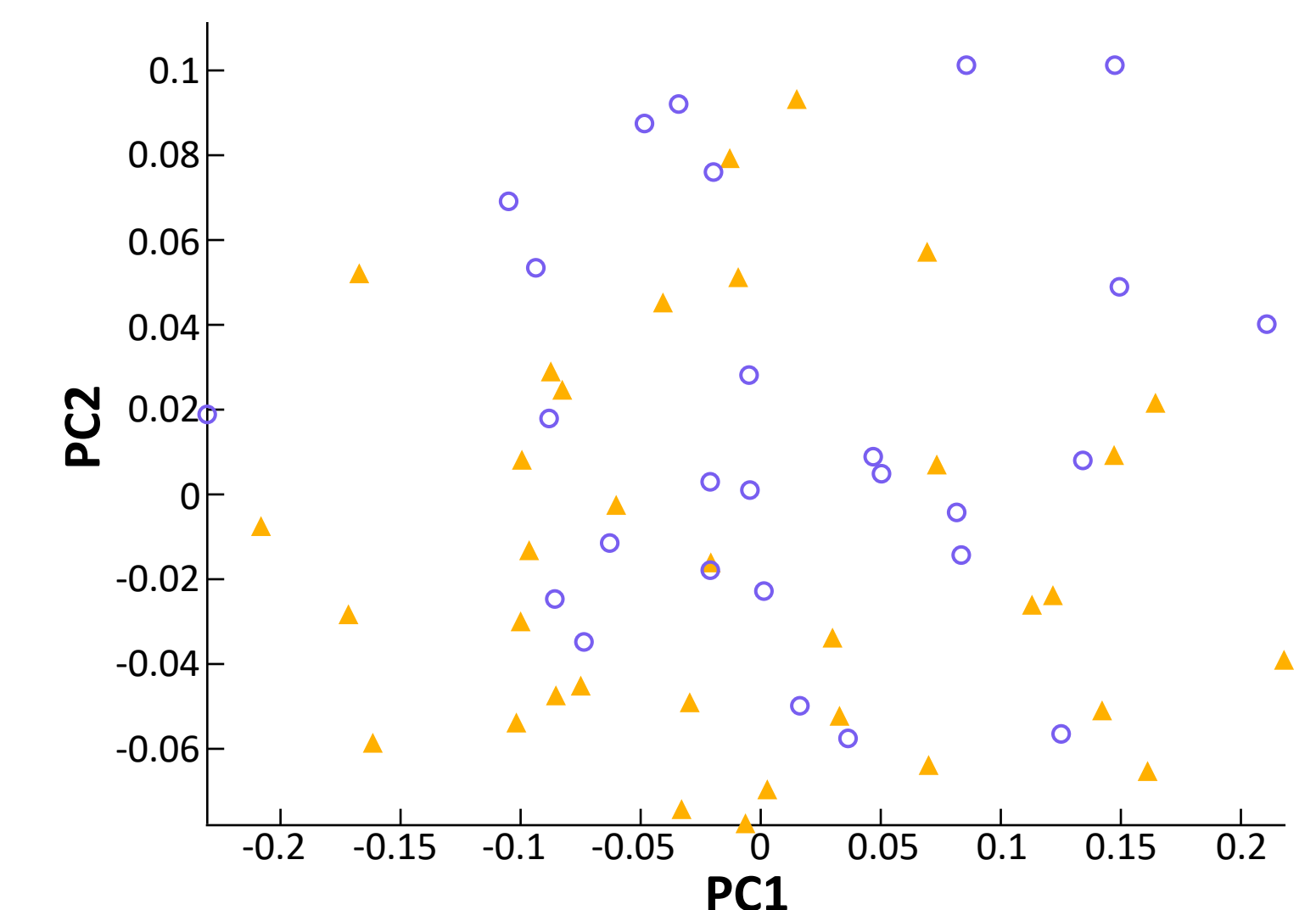
F & M shape significantly different?: Yes ($p=0.01$)*



PC3

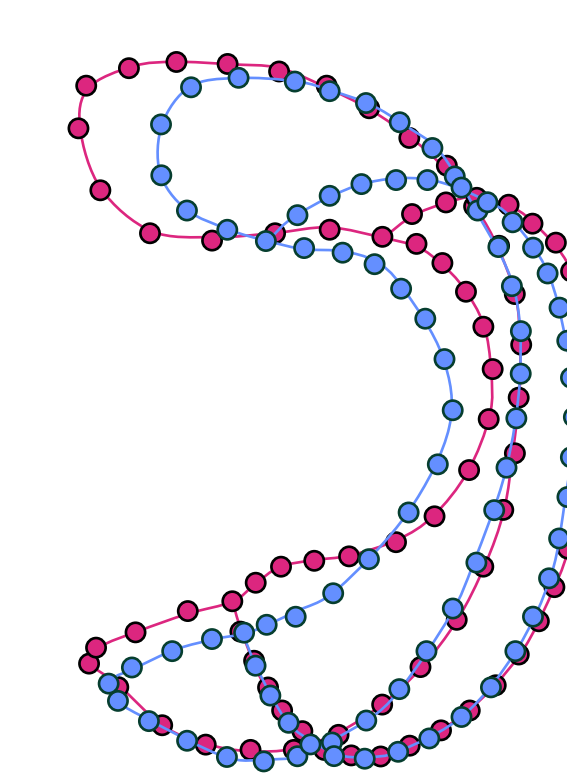
Percent variance: 7.5%

F & M shape significantly different?: No ($p=0.97$)



Shape Variation Associated with Body Size

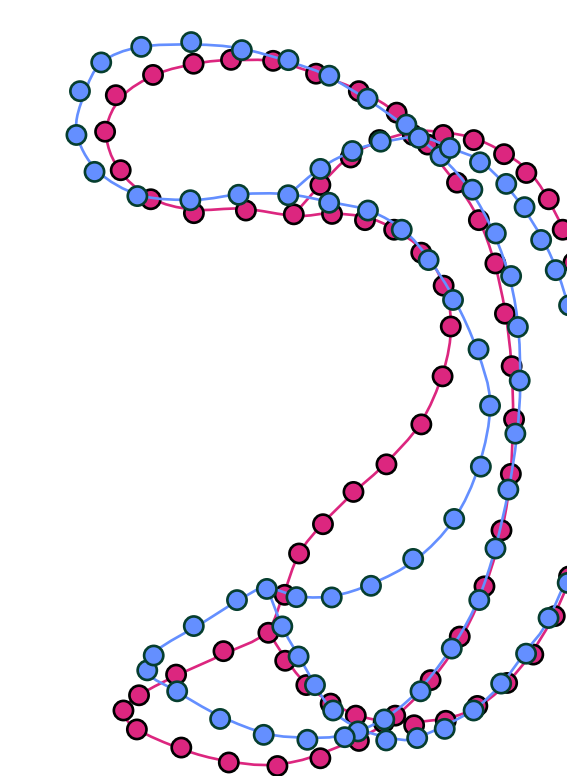
The first three principal components explain over 74% of size-related variation in shape of the medial meniscus. Outlines demonstrating size-related variation in shape at two standard deviations positive (blue) and negative (magenta) are included below. The variation captured along PC1 indicates that the relative length of the anteromedial insertional ligament and the degree of curvature of the meniscal body is related to body size. The size- and sex-related shape differences captured along PC2 indicate that females (♀) have medial menisci with more superiorly projecting upper anterior margins, inner borders that are more s-shaped posteriorly, and posterior roots that are more posteriorly positioned and inferiorly expanded when compared to males (♂; $p<0.001$).



MLTIB PC1

Percent variance: 41.3%

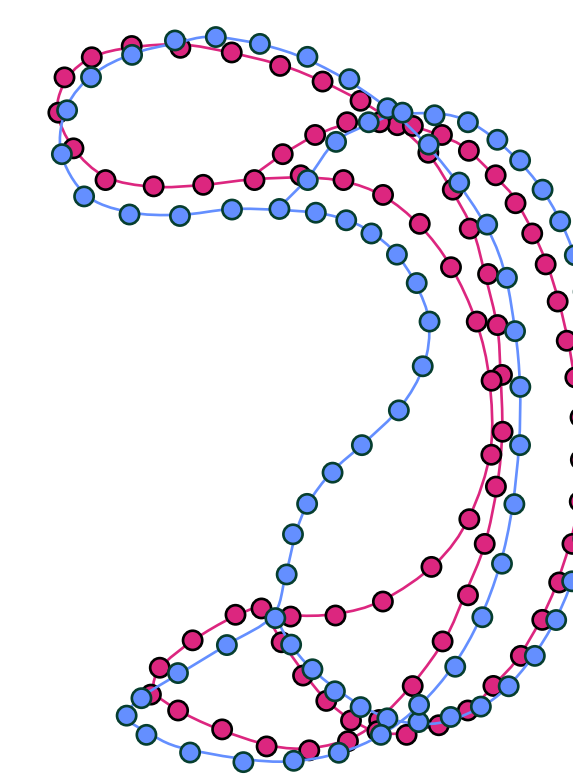
F & M shape significantly different?: No ($p=0.07$)



MLTIB PC2

Percent variance: 25.9%

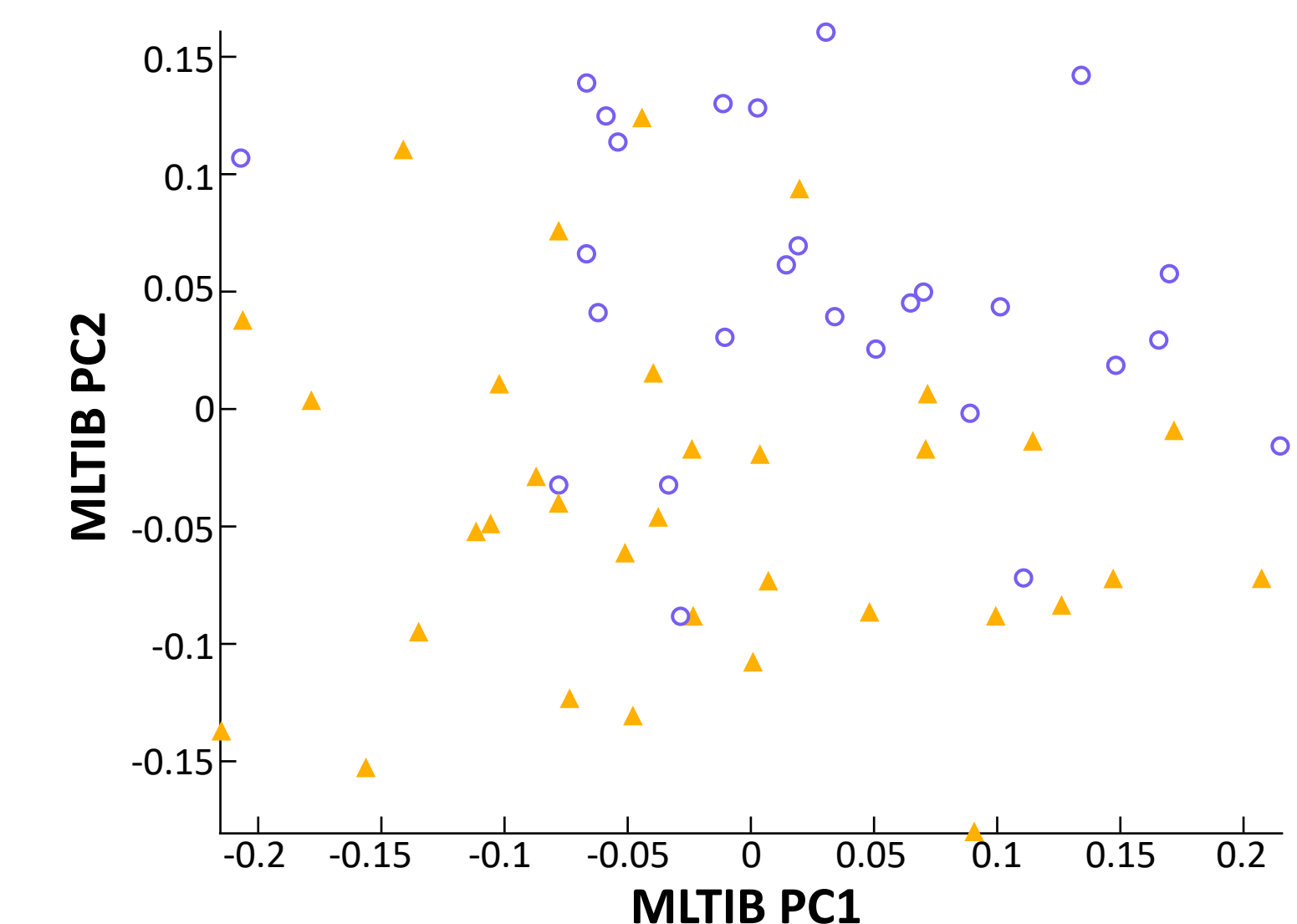
F & M shape significantly different?: Yes ($p<0.001$)*



MLTIB PC3

Percent variance: 6.7%

F & M shape significantly different?: No ($p=0.58$)



Conclusions

These results indicate that body size and its relationship to biological sex play significant roles in observed variation in the shape of the human medial meniscus. Because the shape of anatomical structures is tied to their function, this has important implications for our understanding of knee function in individuals of different biological sexes and body sizes.

Acknowledgements & References

Thank you to the donors for their anatomical gifts as well as the Maryland State Anatomy Board for providing access.

The equipment used for this research was purchased using a generous donation by the Stibel family.

1. Fox AJS, Wanivenhaus F, Burge AJ, Warren RF, & Rodeo SA. (2015). The human meniscus: A review of anatomy, function, injury, and advances in treatment. *Clinical Anatomy*, 28(2).
2. Messner K, & Gao J. (1998). The menisci of the knee joint. Anatomical and functional characteristics, and a rationale for clinical treatment. *Journal of Anatomy*, 193 (Pt 2), 161–178.
3. Frelat MA, Katina S, Weber GW, & Bookstein FL. (2012). Technical note: A novel geometric morphometric approach to the study of long bone shape variation. *American Journal of Physical Anthropology*, 149(4), 628–638.
4. Sylvester AD. (2013). A Geometric Morphometric Analysis of the Medial Tibial Condyle of African Hominids: Hominid Medial Tibial Condyle. *Anatomical Record*, 296(10), 1518–1525.
5. Metashape Professional 1.6.5 (Agisoft, 2020)
6. Artec Studio 16 (Artec3D, 2021)
7. Avizo Lite 9.0.1 (FEI Visualization Sciences Group, 2015)
8. MATLAB R2018b (The MathWorks Inc., 2018)

